Report R79-912658-10

# Laser Welding of Ship Steel

Final report under

Bethlehem Steel Corporation

Purchase Order #1560-917-1531-W

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TABLE OF CONTENTS

# FOREWORD

The purpose of this report is to present the results of one of the resesrch and development programs which was initiated by the members of the ship Production Committee of The Society of Naval Architects and Marine Engineers and financed largely by government funds through a cost-sharing contract between the U. S. Maritime Administration and Bethlehem Steel Corporation. The effort of this project was directed to the development of improved methods and hardware applicable to shipyard welding in the U. S. shipyards.

Mr. W. C. Brayton, Bethlehem Steel Corporation, was the Program Manager; Messsrsl C. M. Banas and G. T. Peters, United Aircraft. Research Laboratories, directed the development at East Hartford, Connecticut.

Special acknowledment is made to the members of Welding Panel SP-7 of the SNAME Ship Production Committee who served as technical advisors in the preparation of inquiries and evaluation of subcontract proposals.

## SUMMARY

An expertimental laser welding investigation was conducted on ship steel. This program was directed toward evalution of practical aspects of laser welding in tine shipyard and represents a follow-on to previous flat-position laser welding tests conducted under optimum joint cleanliness and fitup conditions. In the current program, welds were formed between surfaces with nonperfect fitup, between plasma-cut surfaces, between surfaces deliberately mismatched to provide a varging joint gap and under out-of-position welding conditions.

It was found that the maximum joint gap between l/2-inch-thick pieces which could be effectively bridged by laser welding with filler addition was 1/16 inch.* A satisfactory single-pass' weld bead was formed with such a gap at 15 kW and 35 ipm using 1./16 inch filler wire fed at 150 ipm. Acceptable welds were also formed between plasma arc surfaces which were initially mchine-sanded to remove cut scale.

Out-of-position weld tests were limited to tee joint configurations; a dual-pass weld procedure produced the best results. A l-inch-thick tee joint was effectively welded at 13 kW and 30 ipm in the horizontal position. Tee joints in 3/8-in.-thick material were formed in the vertical-up and vertical-down position. Welds formed under nominal 6 kW, 40 ipm conditions exhibited smooth bead profiles and relatively smooth fillets. Slight improvement in fillet profile was obtained by modest addition of filler material. No apparent difficulty was experienced with out-of-position welding provided that conditions leading to a relatively narrow weld bead were maintained.

*Author,s note: Subsequent to the completion of this program, new techniques were developed which facilitated laser welding with a 0.1 in. gap.

# INTRODUCTION

The rapid development of high-power *laser* welding technology (Refs. 1-3) has suggested its potential utilization for merchant ship construction. Laser welds have been generated in a variety of materials at relatively high speeds and have excellent mechanical, metallurgical and radiographic characteristics. Dual-pass WeldS without filler material have been formed which demonstrate the potential for joining sections appropriate to ship construction.

In a program sponsored by Bethlehem Steel (P.O. #1560-1029-1500-T) (Ref. 4), laser welds were formed in ship steel of 3/8, 5/8, 3/4, 1.0 and l-1/8 inch thickness. Radiographically acceptable welds were obtained with a single pass in plate thicknesses to 5/8 inch; dual-pass welds were used on thicker material. Sound dual-pass welds were obtained in 3/4 inch material; excessive Porosity was noted in laser welds in thicker sections. Mechanical test of the specimens by Bethlehem Steel. indicated acceptable weld properties in materiel to 3/4 inch thick.

In addition to the butt welds noted above, tee welds were also formed using 3/8-inch-thick webs and l/2-inch-thick flanges. Complete fusion of the tee joints was obtained by using dual passes, one from each side of the tee, each at a laser power of 7.5 kW and a welding speed of 65 *ipm.* For these welds the beam was inclined at 6° to the flange.

Machined mating surfaces were used in the program described in Ref. 4 to identify capabilities under ideal conditions. It is clearly understood, however, that *such* fitup is out of the question in shipyard operation and that substantial gaps and plasma- or oxyacetylene-cut edges are the rule. The program described herein was therefore undertaken with the specific objective of identifying laser capability for dealing with the practical, aspects of shipyard applications. This work was undertaken at the request of Bethlehem Steel Corporation under their Purchase Order #1560-917-1531-W in support of Bethlehem’s performance of MARAD Project SPI-7-805.

## EXPERIMANTAL APPARATUS AND PROCEDURE

### Laser Facilities

Two laser units developed at the United Technologies Research Center were used for the tests conducted in this *pogram.* The first is a 10 kW cross-beam system developed under corporate tiding. The unit incorporates unstable oscillator. optics which provide an output beam which exhibits annular energy profile with a magnification ratio (outer-to-inner-diameter ratio) of 2.0.

For 3/8 inch tee welding tests, the beam from the cross-beam laser was directed into a focusing mirror and then horizontally onto the weld seam. The workpiece was clamped to a counterweighted table mounted in the vertical plane. Inert gas shielding of the tee zone was provided with a trailer shield cut to fit the tee configuration.

The second laser unit used in the test program was developed under Navy Contract N60921-70-C-0219 sponsored by the Naval Ordnance Systems Command and is described in detail in Ref. 5. The cross-bean system is equipped with oscillator-amplifier optics which provide a beam with a Gaussian energy distribution.

An 18-inch-focal-length mirror was used for focusing the beam for most tests conducted with the latter laser. In contrast to the moving workpiece arrangement utiltized for the vertical-up and -down tests, the high-power butt and tee weld tests were conducted with a stationary workpiece and moving optics. This mangement is described in Ref. 4 and is felt to more closely simulate the manner in which laser welding would be employed in a shipyard. The moving focus mirror system offers a total travel length of about eight feet and hence has the capability for welding relatively large workplaces. Gas shielding for the high-power tests was provided with a simple trailer shield and plasma suppressor.

### Procedure

In butt welds, the effects of joint gap were evaluated using machined mating surfaces which could be accurately spaced. Plasma-cut surfaces were either wire-brushed or machine-sanded prior to Welding. The material was degreased, rinsed with solvent and compressed air dried. Laser tack welds were formed at- each end of the joint to prevent separation during welding and to insure proper seam alignment with the beam.

Bead-on-plate penetrations were initially formed to establish the applicable range of weld parameters for each material thickness. A standard Linde MIG wire feeder with a maximum feed rate of 1200 ipm was utilized. The wire was directed into the trailing edge of the weld pool at approximately 300 to the material surface.

Due to the rapid solidification of the weld zone, wire placement was critical. The tolerence on wire feed parameters decreased with increasing wire size; 0.035-, 0.045- and 0.062-in.-diameter wire was used.

For tee section welding in the horizontal, vertical-u p and vertical-down positions, the focused beam was directed horizontally into the weld seam. Filler wire was introduced into the trailing edge of the weld pool just behind the beam impingement point. An entrance angle of about 45° to the material surface found to promote a smooth fillet.

A tabulation of significant test points is presented in Table I. Additional butt weld tests were also conducted in l/2-inch-thick material spaced at 3/32 inch. Within the scope of the tests conducted during this program, effective laser welding procedures were not established for this wide gap.

## Discussion of Experimental Results

### A. Flat Position Butt Welds

The objective of this test series was to evaluate the effects of non-ideal joint conditions on laser butt welds. To identify the effects of joint gap, mating edges were initially machined square and parallel. Spacing shims were inserted at each end of the seam between the mating surfaces to provide the desired gap.

Initially, as noted in Table I, a tapering gap from O-5% (0-.025 inch) of the material. thickness was explored. It was found that a sound direct butt weld without filler could be made with a gap to 2% (.01 inch) of the plate thickness. A gap greater than 2% but less than 3% of the thickness produced an underfilled weld. With a gap exceedhg 3% (.015 inch) of the thickness, the beam passed through the joint with essentially no fusion taking place. Although there was a slight carryover of fused material when the weld proceeded from the zero gay side, these results were not markedly affected by weld direction. It is to be concluded that laser welds in l/2-inch-thick material spaced by more than 0.01 inch require filler addition for generation of sound weld geometry.

In contrast to its sensitivity to joint gap, laser welding was found to be relatively tolerant to surface mismatch. Sound bead profiles were obtained with surface mismatch from o-5% of the material thickness. Such welds, made between close-fitting machined surfaces, exhibited good root and face bead reinforcement. Further, the edge of the protruding surface was consumed during the welding process, thereby tending to smooth over the mismatch. It is anticipated that severe mismatch will result in reduction of the depth of the weld interface, but that effective laser welding will. still be possible.

In view of the strong influence of joint gap on weld characteristics, attention was directed to this factor. A 1/64 inch gap, the spacing at which joint underfill was fetid to occur, was initially investigated. As shown in Fig. 1, conditions were readily established for dealing with this gap. A sound weld was formed at 10 kW and 20 ipm using a modest fill of 100 ipm of 0.035-inch-diameter wire. It is noted that the volume of the gap (.0075 $in.^3$/in) was about 60% greater than the volume of wire added (.005 $in.^3$/in.) indicating some lateral plate shrinkage.

Although slight difficulty was experienced with a 1/32 in. gap, desirable welding conditions were established. As noted in Fig. 2, for a representative weld, weld parameters were the same as for a 1/64 in. gap except that 0.045-in.-dia *wire was* used. The bead has a smooth, tapering cross section. Again as with the 1./64 inch gap, the volume of wire added was less than the volume of the initial gap. In this regard, it should be noted that the gap spacing was facilitated by small shims located at the two ends of the weld sample. The center section of the weld region was therefore free to contract. Additional filler may be required under conditions of high panel restraint; this should not present difficulty for 1/64 and 1/32 in gaps.

Substantially more difficulty was experienced with a 1/16 inch gap. For this condition the focused beam diameter (-0.035 inch) is smaller than the width of the opening. Under these conditions the beam tends to pass through the panels without initiating fusion. By slightly favoring one side of the weld (Fig. 1) or by inclining the beam slightly relative to the face of the mating surfaces, it was possible to initiate fusion and establish reasonably sound welds. A I-/16-inch-diameter wire was found to be convenient for this condition.

Attempts to form sound laser welds in gaps broader than 1/16 inch were not successful within the scope of this program. Tests with wire addition with a 3/32 inch gap were unsatisfactory. Similarly, attempts to use preplaced powder filler failed. In this case, violent material eruptions occurred, yielding porous welds. Since gaps to 1./8 inch are common in shipyard applications, additional development of laser welding techniques for such conditions is required.

Additional tests in 1/2 inch material demonstrated Laser weldin g applicability to plasma-arc-cut surfaces. For plasma-are-cut samples, a simple wire-brushhg to remove cut slag was adequate weld prep. Due to the nonperfect fitup, filler material was required to prevent joint Underfill. Local gaps exceeding I/16 inch were tolerable provided the surfaces were generally in contact along the length of the weld.

## B. Vertical Position Tee Welds

Since many shipyard welds are formed out of position, tests were conducted to evaluate the laser's applicability under such conditions. Many Of the OUt-Of-position applications are for tee joints. Accordingly, laser welds were formed in the vertical position in 3/8 inch tee configurations as shown in Figs. 4-6.

Although a full penetration can be obtained in this thickness, dual-pass welds were utilized. Dual-pass welding provides smooth fillets (Fig. 5) and further tends to balance thermal effects so that distortion is minimized (Fig. 4). No difficulty was experienced in forming such welds in either the vertical-up or vertical-down positions. Tolerance to edge prep conditions was similar to that for flat position welding.

Simple bend tests were performed to provide an indication of tee joint integrity. As shown in Fig. 6, good joint strength was indicated despite the small fillet reinforcement. Since the latter condition imposes higher stress loading on the laser weld than on a convention, heavily reinforced, weld in such a bend, the mechanical integrity of the laser joints appears to be quite satisfactory.

C. Horizontal-Position Tee Welds

Horizontal-position tee welds were formed to demonstrate the laser’s capability for joining heavier sections. Sections comprising a 1/2 inch web and a 1 inch flange were joined using both single- and dual-pass welds. The latter provided smoother fillet reinforcement and reduced distortion.

The 1/2/1 inch tee sections were prepared with tight-fitting surfaces, with machined surfaces gapped by l/32 inch, and with wire-brushed or machine-sanded, plasma-arc-cut mating edges. “Sound weld beads were formed under all conditions, provided that adequate filler material was provided.

In addition to the 1/2/1 inch tees, 1/1 inch tees were also joined in the horizontal position. An edge prep as shown in Fig. 7 was used. The beam was directed at 5° to the flange surface. Filler wire was directed into the trailing edge of the molten pool at an angle of approximately 45° to the surfaces.

The weld cross section shown in Fig. 7 indicates good joint integrity. Full fusion of the entire seam was obtained with good tie-in to both members. This result is important in that it demonstrates the capability for adding sufficient filler to substantially modify weld zone chemistry.

## CONCLUDING REMARKS

The work described represents an initial step toward developing laser welding procedures for practical shipyard applications. The process has been shown to be samewhat tolerant to joint gap, to mismatch, to out-of-position conditions and to plasma-arr-cut weld prep. Further, the ability to add substantial filler (relative to the volume of the fusion zone) has been demonstrated.

With further development, it is anticipated that the gap tolerance for *laser* welding of l/2-inch-thick material can be increased from 1./16 to 1/8 inch. Development of such capability would significantly enhance the potential for laser welding for ship construction.

## REFERENCES


1. Breinan, E. M., C. M. Banas and M. A. Greenfield: Laser Welding - The Present Stete of tine Art. United Technologies Research Center Report R75-111087-3, June 1975.

2. Bal, W. C. and C. M. Banas: Welding with a High-Power, $CO_2$ Laser. SAE Paper NO. 740863, October 1974.

3. Banas, C. M.: Laser welding of Navy ship construction Materials. Final Report to Naval Ship Systems Command under Contract NOO024-72-C-5585, August 1973.

4. Banas, C. M. and G. T. Peters: Study of the Feasibility of Laser Welding in Merchant Ship Construction. Final Report to Bethlehem Steel Corporation in support of Betblehems Contract 2-36214 with the U. S. Department of Commerce, August 1974.

5. Brown, C. O., et al: Investigation of a High-Power $CO_2$ Convection Laser. Final report on Navy Contract N60921--70-C-0219, MAY 1, 1972.

TABLE I

## SUMMARY OF PRINCIPAL TESTS

### A. Butt Welds in 1/2-in. Plate

| No. | Power, kW | Weld Speed, ipm | Wire feed, ipm | Test Description | Comment |
|---|---|---|---|---|---|
| 1 | 11 | 30 | | Bead on Plate (BOP) | Heavy Penetration (HP) & Drop Thru (DT) |
| 2 | 10 | 35 | | Bead on Plate (BOP) | Incomplete Penetration (IP) |
| 3 | 11 | 32.5 | | BOP (Al Paint on Surface) | No Improvement Due to Al |
| 4 | 10 | 30 | | 0-5% (of MATL Thickness) gap | O-2% GAP - OK<br>2-3% GAP - Underfill (UF)<br>3-5% GAP - No Fusion |
| 5 | 10 | 25 | | O-5% gap (Out of Focus) | (IP) - No Change In Tolerance to gap |
| 6 | 10 | 30 | | O-5% surface Mismatch | Good Bead Profile |
| 7 | 10 | 25 | | O-5% Surface Mismatch | Good Bead Profile |
| 8 | 10 | 25 | 60 (.035 in. NS-102) | l/64-in. gap | Good Bead Profile |
| 9 | 10 | 20 | 100 (.035 in. NS-102) | l/64-in. gap | Excellent Bead Appearance |
| 10 | 12 | 20 | 300 (.035 in. NS-102) | l/32-in. gap | Underfill (UF) |

TABLE I (Continued)

| No. | Power, kW | Weld Speed, ipm | Wire feed, ipm | Test Description | Comment |
|---|---|---|---|---|---|
| 11 | 12 | 20 | 400 (.035 in. NS-102) | 1/32-in. gap | Uneven Bead |
| 12 | 12 | 20 | 400 (.035 in. NS-102) | 1/32-in. gap, out-of-focus | Incomplete Penetration |
| 13 | 12 | 20 | 100 (.045-in, NS-102) | 1/32-in. gap | Good Bead Profile Full Penetration |
| 14 | 12 | 35 | 300 (.045-in. NS-102) | 1/16-in. gap | Underfilled |
| 15 | 12 | 30 | 600 (.045-in. NS-102) | 1/16-in. gap | Broad Top Bead, IP |
| 16 | 12 | 30 | 600 (.045-in. NS-102) | 1/16-in. gap | High Bead Crown, IP |
| 17 | 12 | 30 | 500 (.045-in, NS-102) | 1/16-in. gap | Underfilled |
| 18 | 15 | 25 | 150 (.062 E70-T-1) | 1/16-in. gap | Underfilled |
| 19 | 15 | 25 | 250 (.062 E70-T-1) | 1/16-in. gap | Slight UF, IP |
| 20 | 15 | 20 | 300 (.062 E70-T-1) | 1/16-in. gap | Good Penetration, UF |

TABLE I (Continued)

| No. | Power, kW | Weld Speed, ipm | Wire feed, ipm | Test Description | Comment |
|---|---|---|---|---|---|
| 21 | 15 | 25 | 300 (.062 E70-T-1) | l/16-in. gap | Irregular Drop Through |
| 22 | 15 | 35 | 150 (.062 E70-T-1) | l/16-in. gap | Good Bead Profile |
| 23 | 12.5 | 30 | 900 (.035 NS-102) | l/16-in. gap | Beam Inclined: Centerline Through Top Corner of One Edge & Bottom Corner of Mating Edge. Good Bead. |
| 24 | 12.5 | 30 | | Plasma Cut Machine Sanded | Irregular Bead |
| 25 | 12.5 | 30 | 90 (0.045 in. dia E705 Wire) | Plasma Cut Machine Sanded | IP |
| 26 | 14 | 30 | 30 (.045 in. dia E705 Wire) | Plasma Cut Machine Sanded | Marginal Penetration |
| 27 | 14 | 30 | 30 (0.045 in. dia E705 Wire) | Plasma Cut Machine Sanded | Good Bead |
| 28 | 14 | 30 | 30 (0.045 in. dia E705 Wire) | Plasma Cut Wire Brushed 0-1/64 gap | UF in Spots |

TABLE I (Continued)

| No. | Power, kW | Weld Speed, ipm | Wire feed, ipm | Test Description | Comment |
|---|---|---|---|---|---|
| 29 | 15.2 | 25 | 125<br>(0.045 in. dia<br>E705 Wire) | Plasma Cut<br>Wire Brushed<br>0-1/64 gap | Heavy Top Bead Reinforcement<br>Good Penetration |
| 30 | 10 | 25 | - | Plasma Cut<br>Wire Brushed<br>∿ 1/32 in. gap<br>Seam Filled<br>With Powder Metal | Erratic Interaction,<br>Spatter, Holes, Etc. |
| 31 | 10 | 40 | - | Plasma Cut, Wire Brushed<br>∿ 1/32 in. gap<br>Seam Filled With Powder<br>Metal, Dual Pass | Fair-Porosity<br>Evident |
| 32 | 10 | 60 | - | Plasma Cut, Wire Brushed<br>∿ 1/32 in. gap<br>Seam Filled With Powder<br>Metal, Dual Pass | Spatter,<br>Porosity |

TABLE I (Continued)

B. 3/8-in. Tees-Vertical-Up and Down Positions

| No. | Power, kW | Weld Speed, ipm | Beam Angle To Flange, Deg | Test Description | Comment |
|---|---|---|---|---|---|
| 1 | 12.5 | 60 | 15 | Tight Fitup<br>Vertical UP (VU) | Beam Penetrated<br>Into Flange |
| 2 | 12.5 | 90 | 15 | Tight Fitup<br>Vertical UP (VU) | Beam Penetrated<br>Into Flange |
| 3 | 12.5 | 60 | 10 | Tight Fitup<br>Vertical UP (VU)<br>Beam Spot Slightly<br>Favoring Web | Improved |
| 4 | 12.5 | 60 | 5 | 0.2 in. out of focus<br>(VU) | Full Penetration |
| 5 | 10 | 75 | 5 | Al Paint Added | Good Fillet Front<br>Fair Fillet at Back |
| 6 | 10 | 75 | 5 | Spot Favoring Web,<br>Vertical Down (VD) | Good Bead |
| 7 | 10 | 75 | 5 | Grit Blast<br>Plasma Cut Surface - (VU) | Full Penetration<br>One Blow Hole in<br>8-in. Weld |
| 8 | 10 | 75 | 5 | Base of Web<br>Sanded, (VU) | Front Bead OK -<br>Back Bead Heavily<br>Oxidized |
| 9 | 7 | 40 | 8 | Dual Pass - (VU) | Good |

TABLE I (Continued)

| No. | Power, kW | Weld Speed, ipm | Beam Angle To Flange, Deg | Test Description | Comment |
|---|---|---|---|---|---|
| 10 | 7 | 40 | 8 | Dual Pass - (VU) 80 ipm, .035-in. dia NS-102 Wire | Good Fillet Inadequate Penetration |
| 11 | 8 | 40 | 8 | Dual Pass - (VU) 80 ipm, .035-in. dia NS-102 Wire | OK |
| 12 | 8 | 30 | 8 | l/32-in. gap 150 ipm, .035-in. dia NS-102 Wire | Fair |
| 13 | 8 | 30 | 8 | O-O.02 gap - (VU), 100 ipm- .035-in. dia NS-102 Wire | Good |
| 14 | 7 | 40 | 8 | Dual Pass Tight Fitup Vertical Down | Good Bead |

## LASER WELD IN SHIP STEEL

(1/64) IN. JOINT GAP)

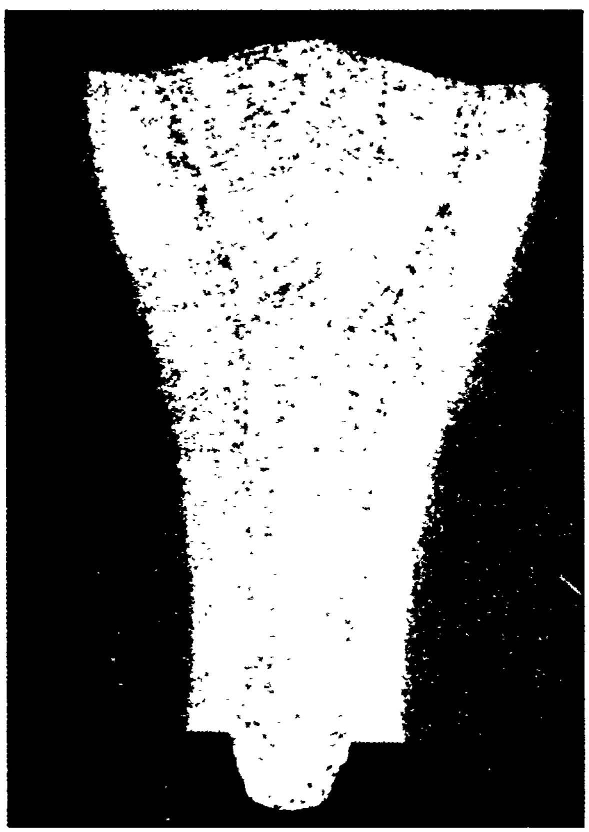
LASER POWER: 10 kW

WELD SPEED: 20 ipm

WIRE: 0.035 IN. NS-102

WIRE SPEED: 100 ipm

MATERIAL THICKNESS: 1/2 IN.



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## LASER WELD IN SHIP STEEL

**(1/32)IN. JOINT GAP)**

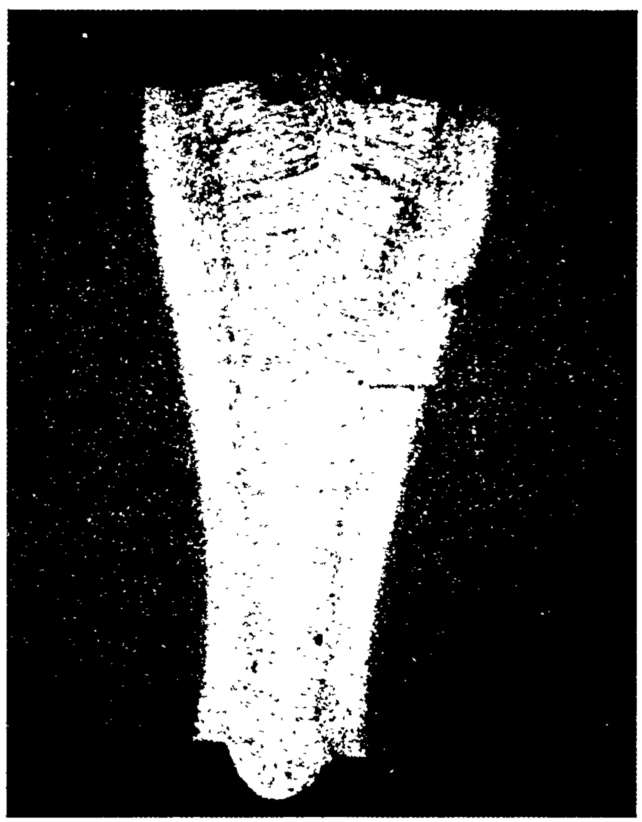
**LASER POWER: 10 kW**

**WELD SPEED: 20 ipm**

**WIRE. 0.045 IN. NS-102**

**WIRE SPEED: 100 ipm**

**MATERIAL THICKNESS: 1/2 IN.**



# LASER WELD IN SHIP STEEL

**(1/16) IN. JOINT GAP)**

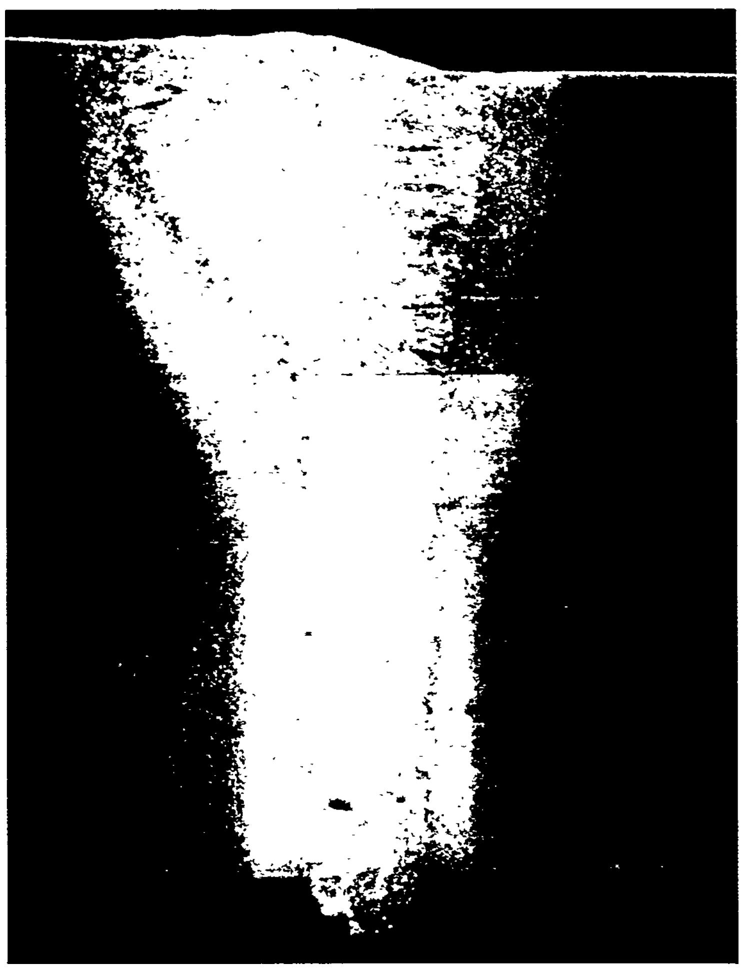
**LASER POWER: 15 kW**

**WELD SPEED: 35 ipm**

**WIRE 1/16 IN. AWS-E-70-T-1**

**WIRE SPEED: 150 ipm**

**MATERIAL THICKNESS 1/2 IN.**



# LASER TEE WELD CHARACTERISTICS

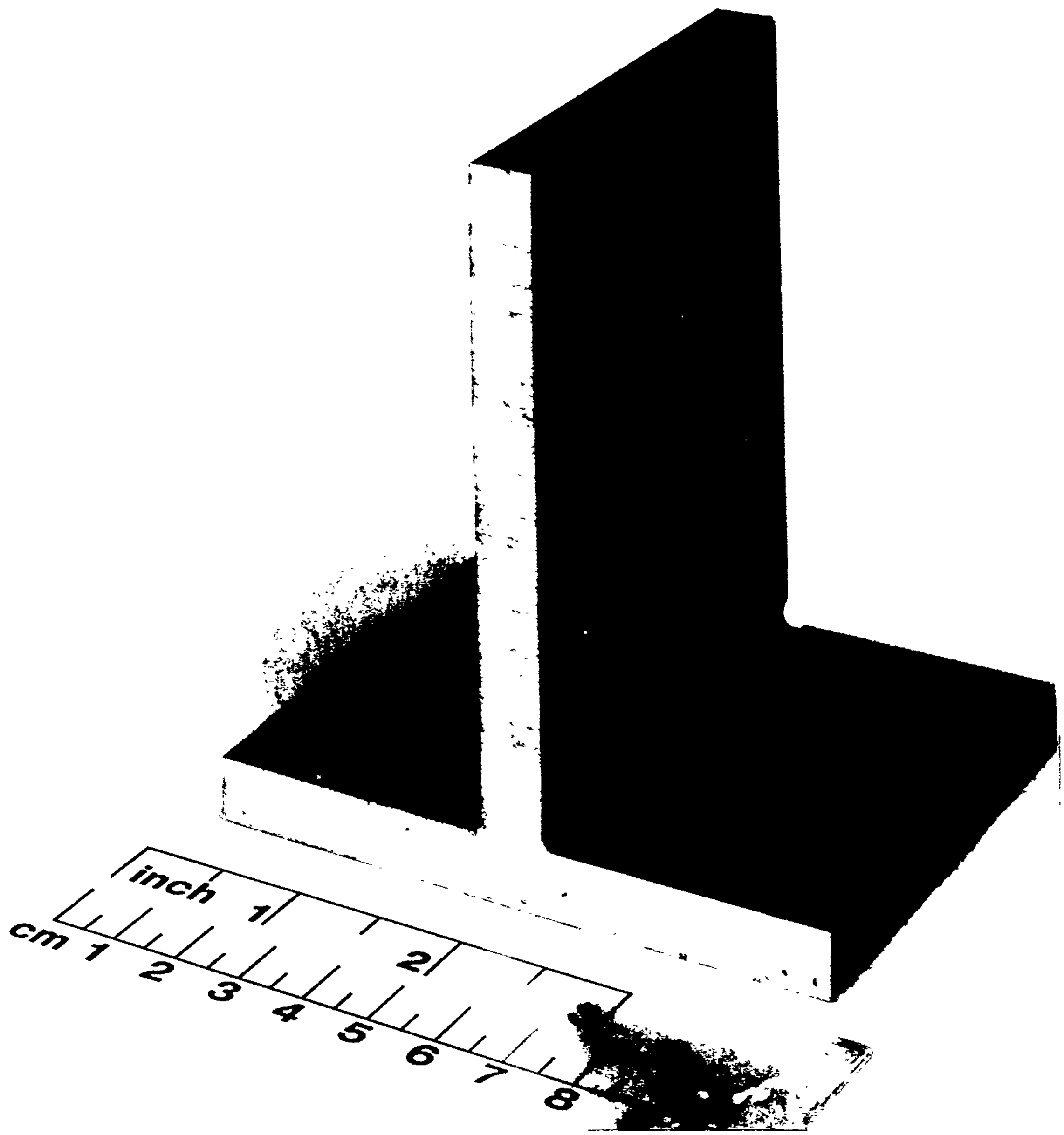
**LASER POWER: 6kW**

**WELD SPEED: 40 ipm**

**NO. PASSES: 2**

**WELD POSITION: VERTICAL UP**

**MATERIAL THICKNESS: 3/8 IN.**




79–12-79–5

# LASER TEE WELD CHARACTERISTICS

LASER POWER: 6kW

WELD SPEED: 40 ipm

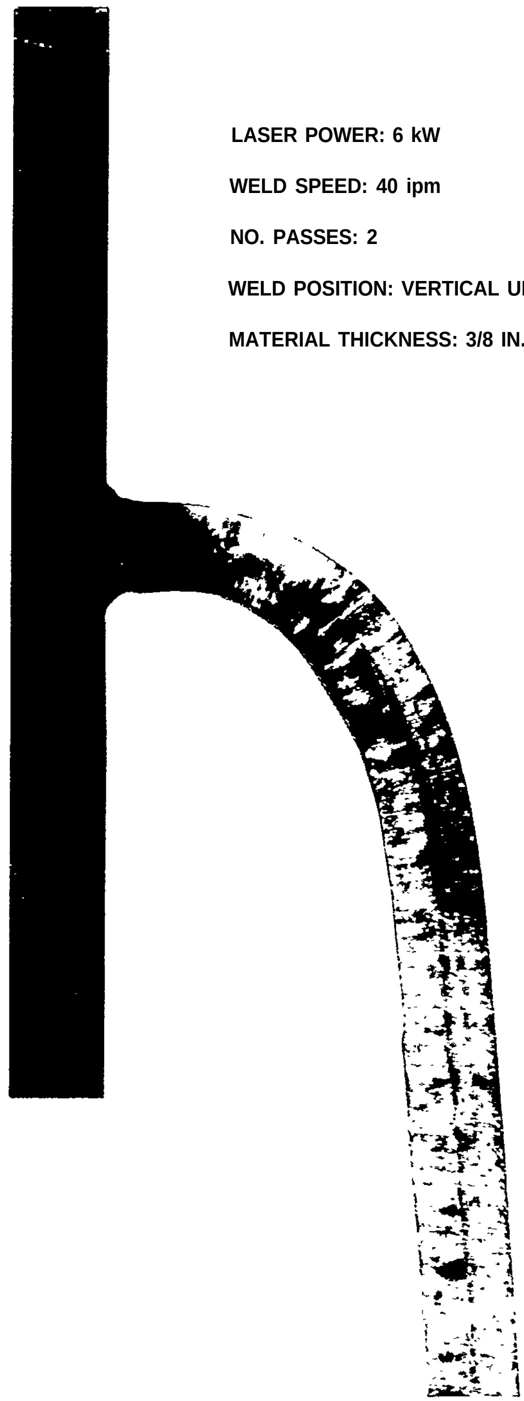
NO. PASSES 2

WELD POSITION: VERTICAL UP

MATERIAL THICKNESS: 3/8 IN.

FIG. 6

## LASER TEE WELD BEND TEST SPECIMEN



LASER POWER: 6 kW

WELD SPEED: 40 ipm

NO. PASSES: 2

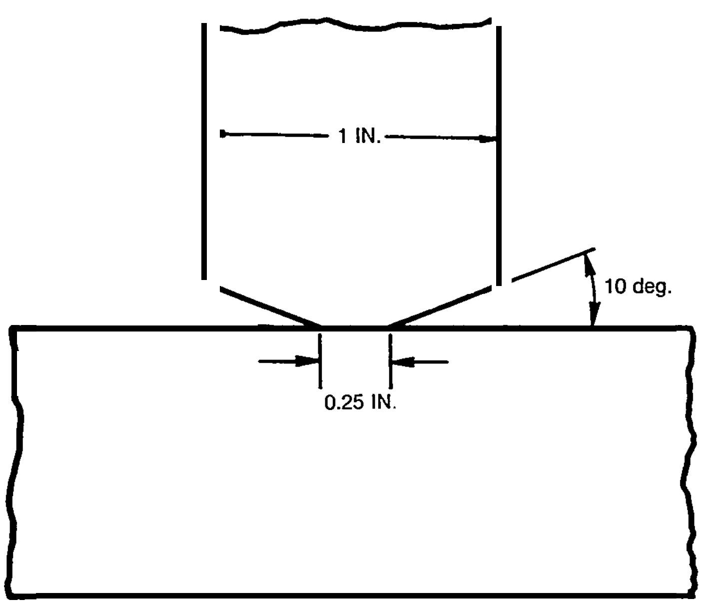
WELD POSITION: VERTICAL UP

MATERIAL THICKNESS: 3/8 IN.

## TEE WELD WITH FILLER

LASER POWER: 13 kW
WELD SPEED: 30 ipm
WIRE SPEED: 300 ipm
WELD POSITION: HORIZONTAL

WELD CROSS SECTION




WELD JOINT PREP

79–12–105–1

GI

GENERAL RI

SHIP DESIGN IM

AUTOKON '71 ● SHIP PI

COMPUTER AIDS TO SHIP

SHIP DESIGN IMPROVEM

WELDING PROGRAM ●

SURFACE PREPARATION A

SHIP DESIGN IM

COMPUTER AI

MATERIALS H/

W